Long CPI Wideband GMTI

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Abstract The conventional approach to GMTI uses narrowband signals and a short coherent processing interval (CPI). In this talk, we examine some of the fundamental theoretical issues involved in GMTI with wideband signals and long CPIs (WL-GMTI). The possibility of wideband, long CPI GMTI has received some attention in recent years, and there are a number of potential benefits:

1) Improved minimum detectable velocity (MDV).
2) Detection of targets with zero radial velocity (but non-zero tangential velocity.
3) Better fit with dual-use SAR/GMTI architectures.
4) Less demanding array requirements (shorter and/or sparser arrays).
5) Greater robustness to clutter internal motion.

The most convenient framework for WL-GMTI is a “post-SAR” architecture, where each spatial channel is pre-processed with synthetic aperture radar (SAR) image processing. The post-SAR architecture is the natural generalization of post-Doppler STAP to the wideband, long-CPI case.

Exact steering vectors in the post-SAR framework are computed analytically for constant-velocity targets, assuming a calibrated array. The steering vectors can be used with algorithms such as the GLRT or AMF to perform adaptive detection on the post-SAR data. We also derive a simple, exact expression for SINR loss when the covariance is known exactly. The loss is a two-dimensional function of both target velocity components, indicating the capability to detect both radial and non-radial target motion.

The final section of this talk examines WL-GMTI performance bounds based on optimal Bayesian detection. In particular, we study how detection performance varies as a function of the number of pixels that the moving target "smears" over in the SAR image. There is a surprising improvement in detection performance when the clutter has strong non-Gaussian tails. In at least some cases, it appears that much of the performance can be achieved with a simple sub-optimal detector.

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Wideband, Long-CPI GMTI

Ali F. Yegulalp

12th Annual ASAP Workshop
16 March 2004

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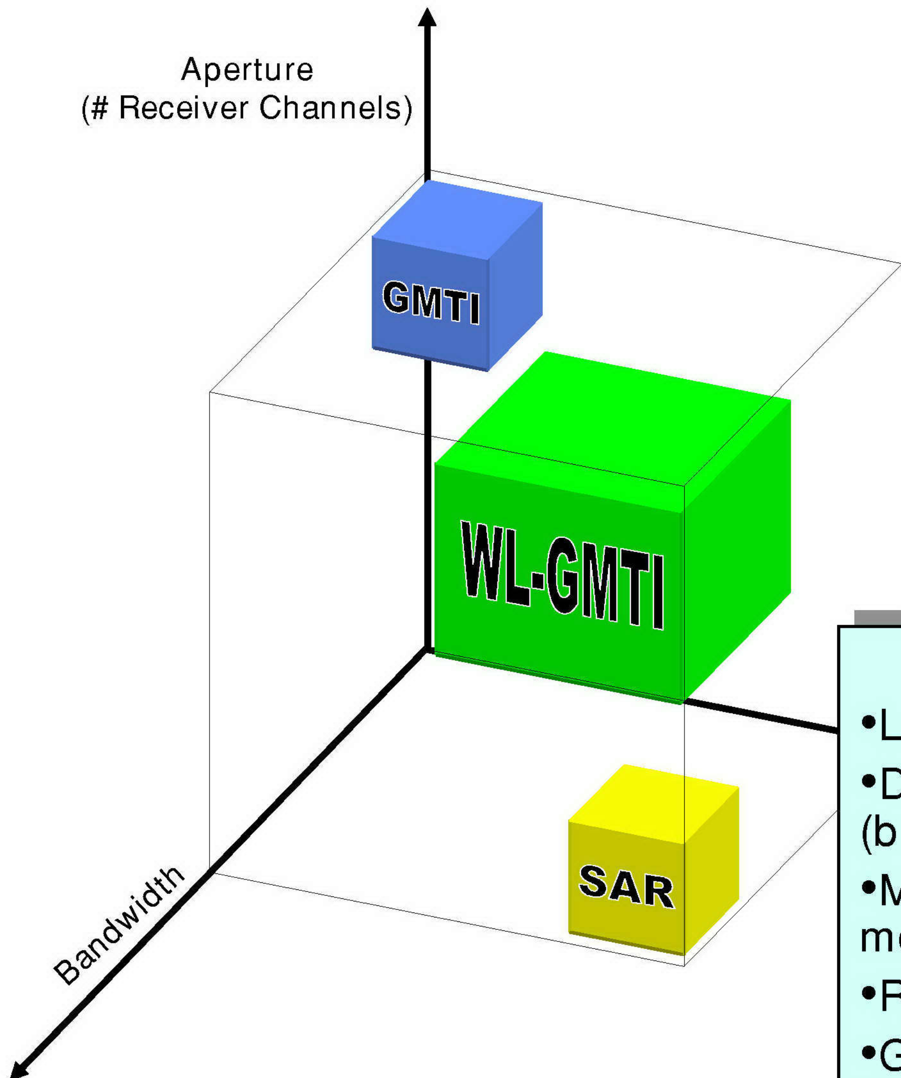
Wideband, Long-CPI GMTI (WL-GMTI)



Premise:

Combine physical aperture of GMTI with bandwidth and integration time of high-resolution SAR.

Purpose:

Supplement traditional SAR and GMTI modes by detecting slow and/or low RCS moving targets.

Potential Benefits:

- Lower minimum detectable velocity (MDV)
- Detection of targets with zero radial velocity (but non-zero tangential velocity)
- More efficient use of radar resources in multi-mode SAR/GMTI platforms
- Reduced array requirements (sparser/shorter)
- Greater robustness to clutter internal motion

Background and References

- J.K. Jao, J. Tsay, and S. Ayasli, "Single-Aperture SAR Detection of Moving Targets," *Proc. 2001 MSS Tri-Service Radar Sym.*, John Hopkins Univ., Maryland, May 2001 (SECRET).
- J. Franz, A. Yegulalp, J.K. Jao, and Serpil Ayasli, "Adaptive Airborne Radar Detection of Moving Targets Under Foliage," *Proc. 2001 MSS Tri-Service Radar Sym.*, John Hopkins Univ., Maryland, May 2001 (SECRET).
- J.K Jao, "Theory of Synthetic Aperture Radar Imaging of a Moving Target," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 39, no. 9, pp. 1984-1992, September 2001.
- J.K. Jao, T.J. Murphy, "Results of the Foliage Penetration Radar and Electronic Support Measures Synergy for Targeting (FOREST) Test Bed Point Design Study," Lincoln Laboratory Project Report FPR-9, October 2001.
- A.F. Yegulalp, "FOPEN GMTI Using Multi-Channel Adaptive SAR," *10th Annual ASAP Workshop*, Lincoln Laboratory, Lexington, Massachusetts, March 2002.
- A.F. Yegulalp, "Analysis of SAR Image Formation Equations for Stationary and Moving Targets," Lincoln Laboratory Project Report FPR-14, June 2002 (Distribution Unlimited).
- J.K. Jao, A.F. Yegulalp, J.R. Franz, and S. Ayasli, "New Results of Airborne Multi-Channel Radar Detection of Moving Targets Under Foliage," 48th *Tri-Service Radar Sym.*, Naval Post-Graduate School, Monterey, California, June 2002 (SECRET).

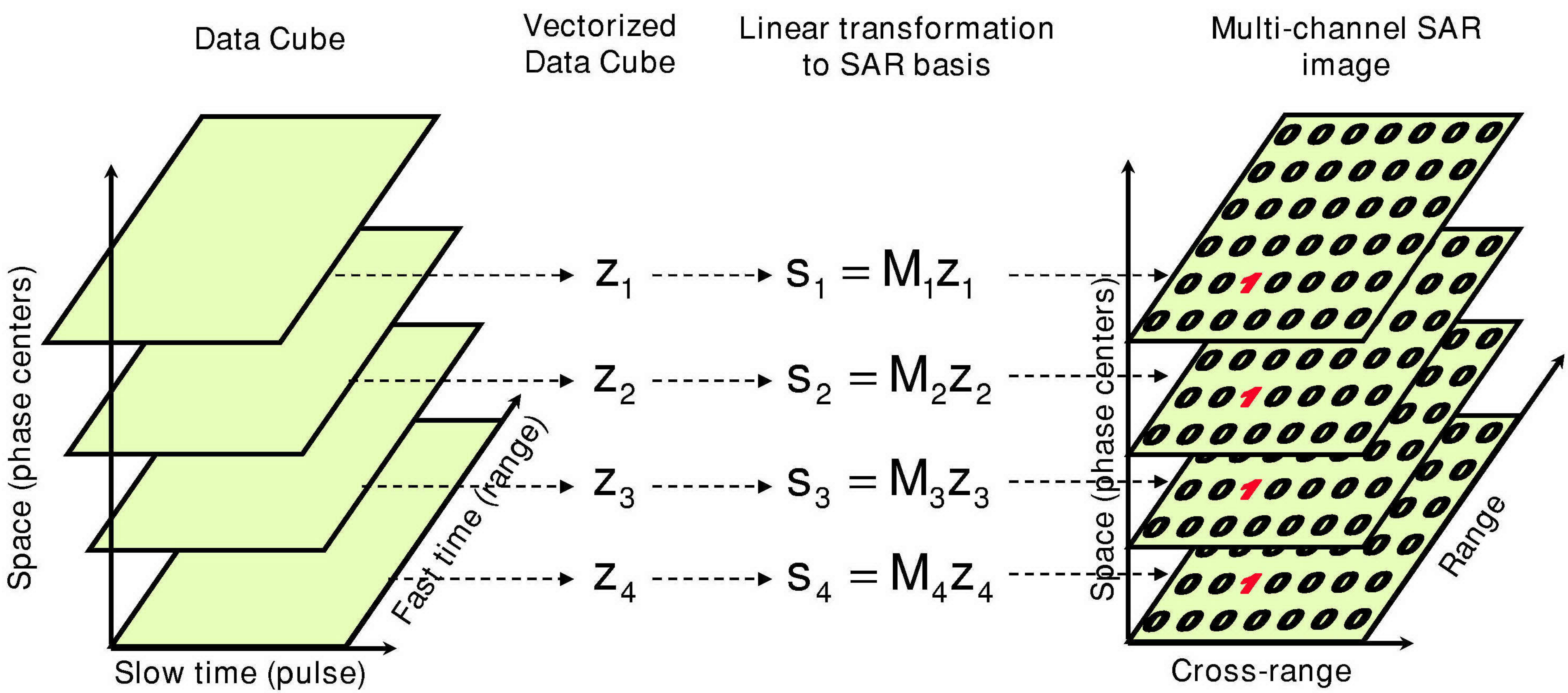
Purpose of this Talk

- Develop a basic framework for discussing and analyzing WL-GMTI
- Show how some of the basic tools of adaptive processing translate to WL-GMTI
  - Steering vectors
  - SINR loss
  - Detection
- Stimulate further interest and work!

Outline

- SAR as the WL-GMTI pre-processor
- WL-GMTI steering vectors
- SINR loss prediction for WL-GMTI
  - Theory
  - Examples
- Detection
- Summary

SAR Pre-processing



Stagger data in slow time to meet DPCA condition

SAR processor knows locations of phase centers

Each SAR resolution cell is automatically "phased up" for stationary clutter at that location

Properties

- SAR is the wideband, long-CPI generalization of the Doppler processor in ordinary post-Doppler STAP
- Linear transform of input data cube
  - Annihilates the exoclutter subspace
  - Invertible transformation of the endoclutter subspace
- "Freezes" clutter into SAR resolution bins
  - Clutter in one bin is well-decorrelated from other bins multiple resolution cells away.
  - Stationary targets have trivial steering vectors
  - Stationary clutter has trivial covariance
- Moving targets smear over multiple resolution cells

Benefits of High Resolution for GMTI

- Target-to-clutter and target-to-noise ratio improve with increasing resolution
  - Improvement holds at least until target is resolved
  - Improvement can continue further if target contains small dominant scatterers
- High spatial resolution provides more clutter per unit area for training adaptive processor
  - Can train in both range and azimuth
- Abundance of training data facilitates more powerful adaptive processing methods
  - Algorithms with more adaptive DOFs
  - Automated data editing to eliminate potential movers from training data

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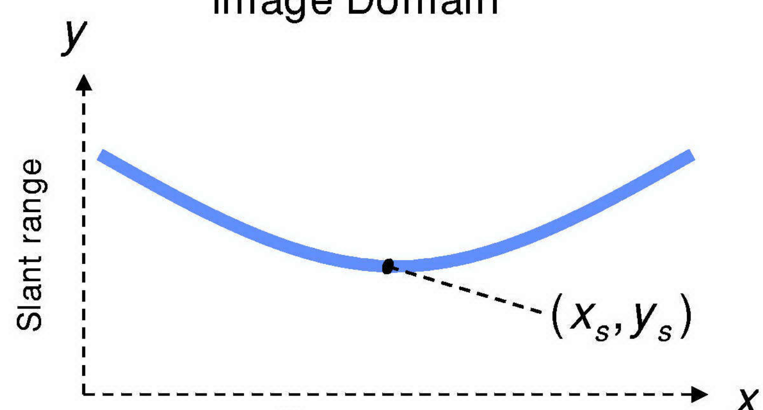
SAR Steering Vector*

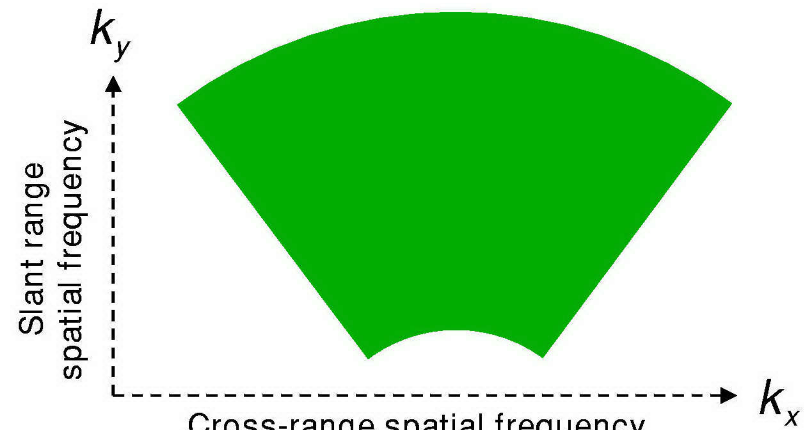
Constant Velocity Point Target

Image Domain



$$\frac{1}{\varepsilon}(x - x_s)^2 + y^2 = y_s^2$$

Spatial Frequency Domain



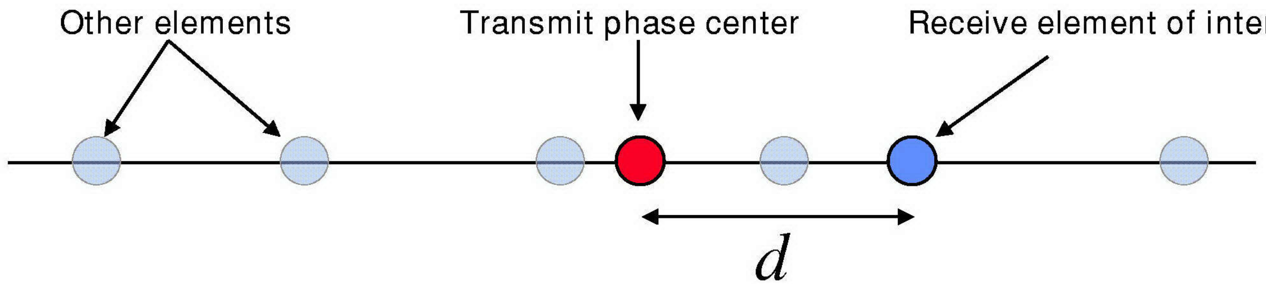
$$G(k_x, k_y) = \frac{k_y}{\gamma\sqrt{k_y^2 + \varepsilon k_x^2}} e^{-ix_s k_x - iy_s\sqrt{k_y^2 + \varepsilon k_x^2}}$$

$$\gamma = \frac{\left\| \mathrm{v}_{\text{target}} - \mathrm{v}_{\text{platform}} \right\|}{\left\| \mathrm{v}_{\text{platform}} \right\|} \qquad \varepsilon = 1 - \frac{1}{\gamma^2}$$

*"Analysis of SAR Image Formation Equations for Stationary and Moving Targets," A.F. Yegulalp, Lincoln Laboratory Project Report FPR-14, 20 June 2002 (Distribution Unlimited)

WL-GMTI Steering Vector

Constant Velocity Point Target



$$x_s(d) = x_s(0) + \frac{d}{2}\left(1 - \frac{1}{\gamma}\cos\psi\right)$$

$$y_s(d) = y_s(0) - \frac{d}{2}\sin\psi$$

$$\gamma = \frac{\left\| \mathrm{v}_{\mathrm{target}} - \mathrm{v}_{\mathrm{platform}} \right\|}{\left\| \mathrm{v}_{\mathrm{platform}} \right\|} \qquad \varepsilon = 1 - \frac{1}{\gamma^2}$$

$$\cos\psi = \frac{\left(\mathrm{v}_{\mathrm{platform}} - \mathrm{v}_{\mathrm{target}}\right)\cdot \mathrm{v}_{\mathrm{platform}}}{\left\| \mathrm{v}_{\mathrm{platform}} - \mathrm{v}_{\mathrm{target}} \right\| \left\| \mathrm{v}_{\mathrm{platform}} \right\|}$$

$$G(k_x, k_y; d) = \frac{k_y}{\gamma\sqrt{k_y^2 + \varepsilon k_x^2}}\, e^{-i x_s(d) k_x - i y_s(d)\sqrt{k_y^2 + \varepsilon k_x^2}}$$

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Simplifying Assumptions

- Large clutter-to-noise ratio
- Elements are mutually calibrated
- No internal clutter motion, crab, unmeasured aircraft motion and vibration
- No jammers and other interference
- Isotropic element patterns
- Optimal AMF processing with perfect knowledge of steering vectors and clutter covariance

Clutter-Limited SINR Loss Calculation

Target steering vector

$$u = \sum_{n=1}^{N} v(n) \otimes e(n)$$

Vectorized target image from n-th channel

Element space basis vector

$$e(1) = \begin{pmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, e(2) = \begin{pmatrix} 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \ldots \; e(N) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 1 \end{pmatrix}$$

$$e = \sum_{n=1}^{N} e(n)$$

Clutter + noise covariance

$$R = \sigma_n^2 I \otimes I + R_c \otimes ee^H$$

Noise power

Clutter pixel-space covariance

Inverse covariance

$$R^{-1} = \frac{1}{\sigma_n^2} I \otimes I - \frac{1}{\sigma_n^4}\left(R_c \left(I + \frac{N}{\sigma_n^2} R_c \right)^{-1} \right) \otimes ee^H$$

Large clutter-to-noise limit

$$\sigma_n^2 R^{-1} \xrightarrow[\sigma_n^2 \to 0]{} I \otimes I - \frac{1}{N} I \otimes ee^H$$

SINR loss

$$\sigma_n^2 \frac{u^H R^{-1} u}{u^H u} = 1 - \frac{\left\| \sum_{n=1}^{N} v(n) \right\|^2}{N \sum_{n=1}^{N} \left\| v(n) \right\|^2}$$

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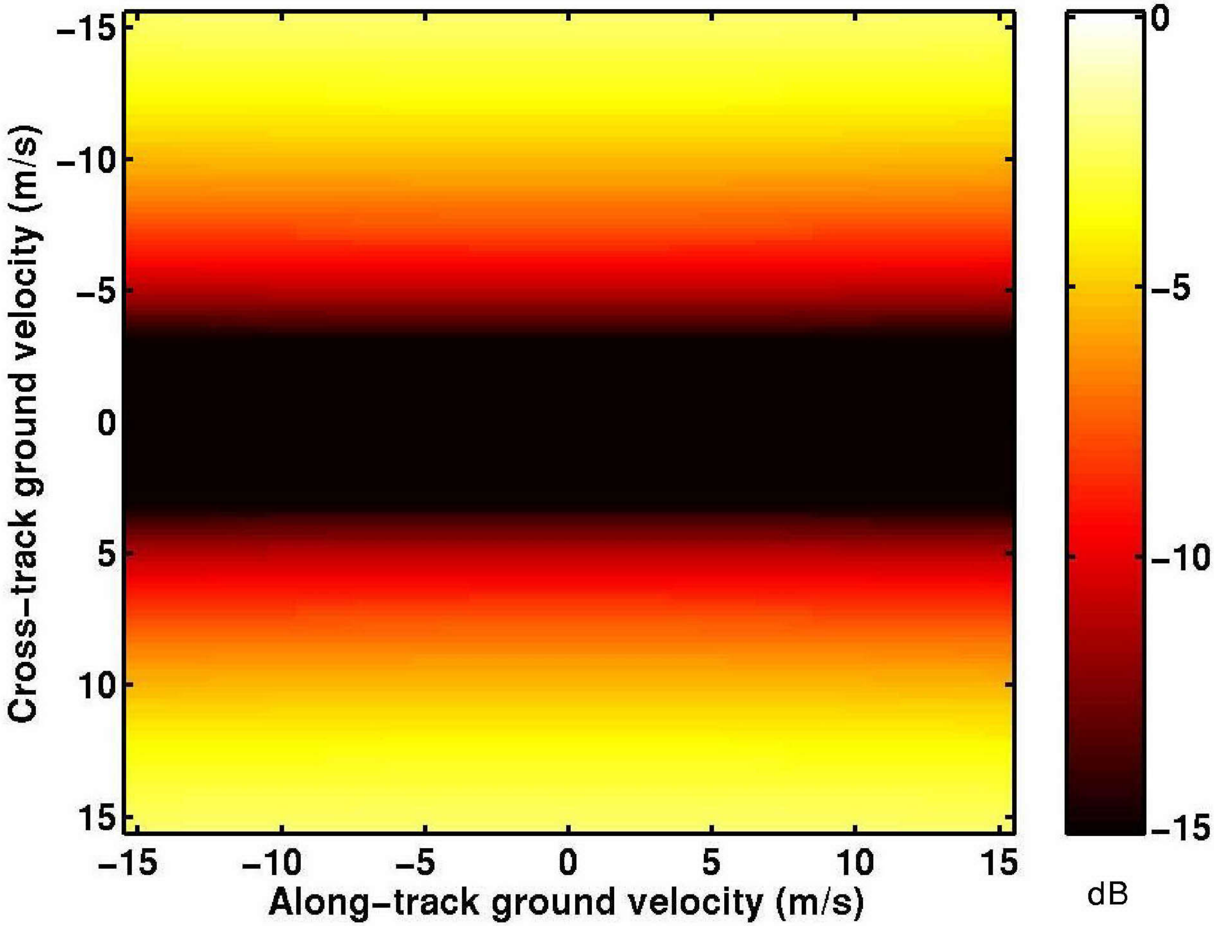
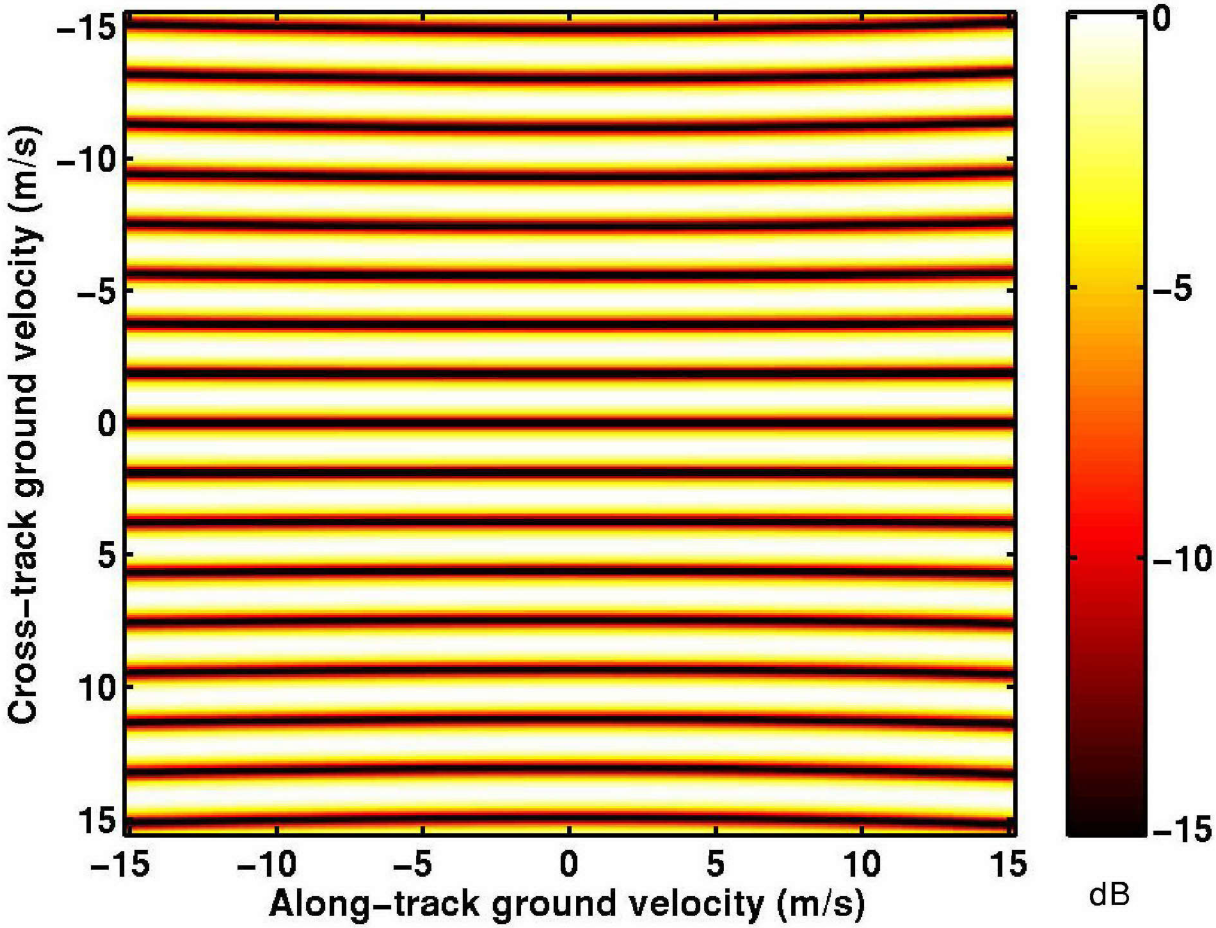
SINR Loss Example



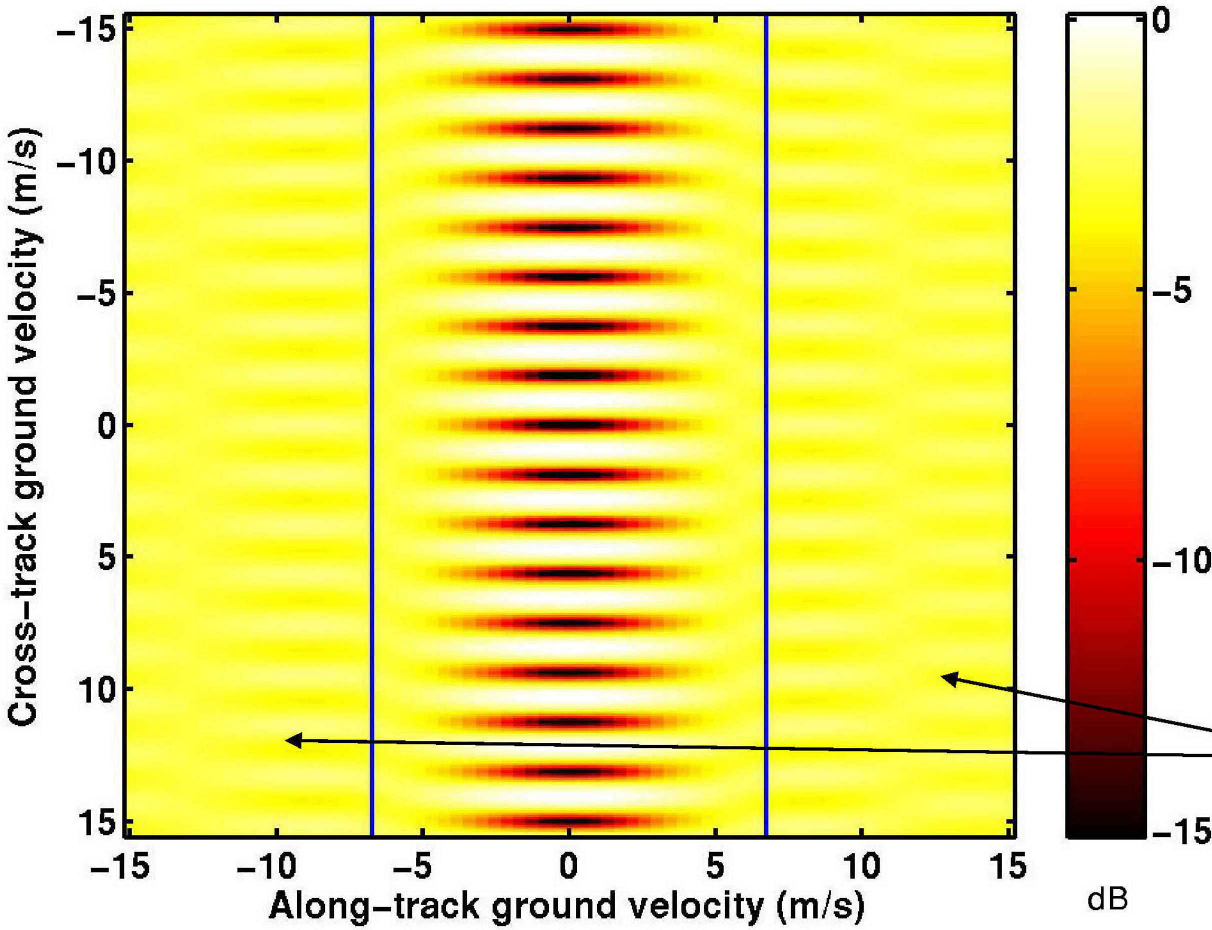
- Carrier = 1 GHz
- Bandwidth = 10 MHz
- CPI = 50 ms
- Range = 10 km
- Airspeed = 180 m/s
- Phase center locations = [0,1] m

SINR Loss Example



- Carrier = 1 GHz
- Bandwidth = 10 MHz
- CPI = 50 ms
- Range = 10 km
- Airspeed = 180 m/s
- Phase center locations = [0,30] m

SINR Loss Example

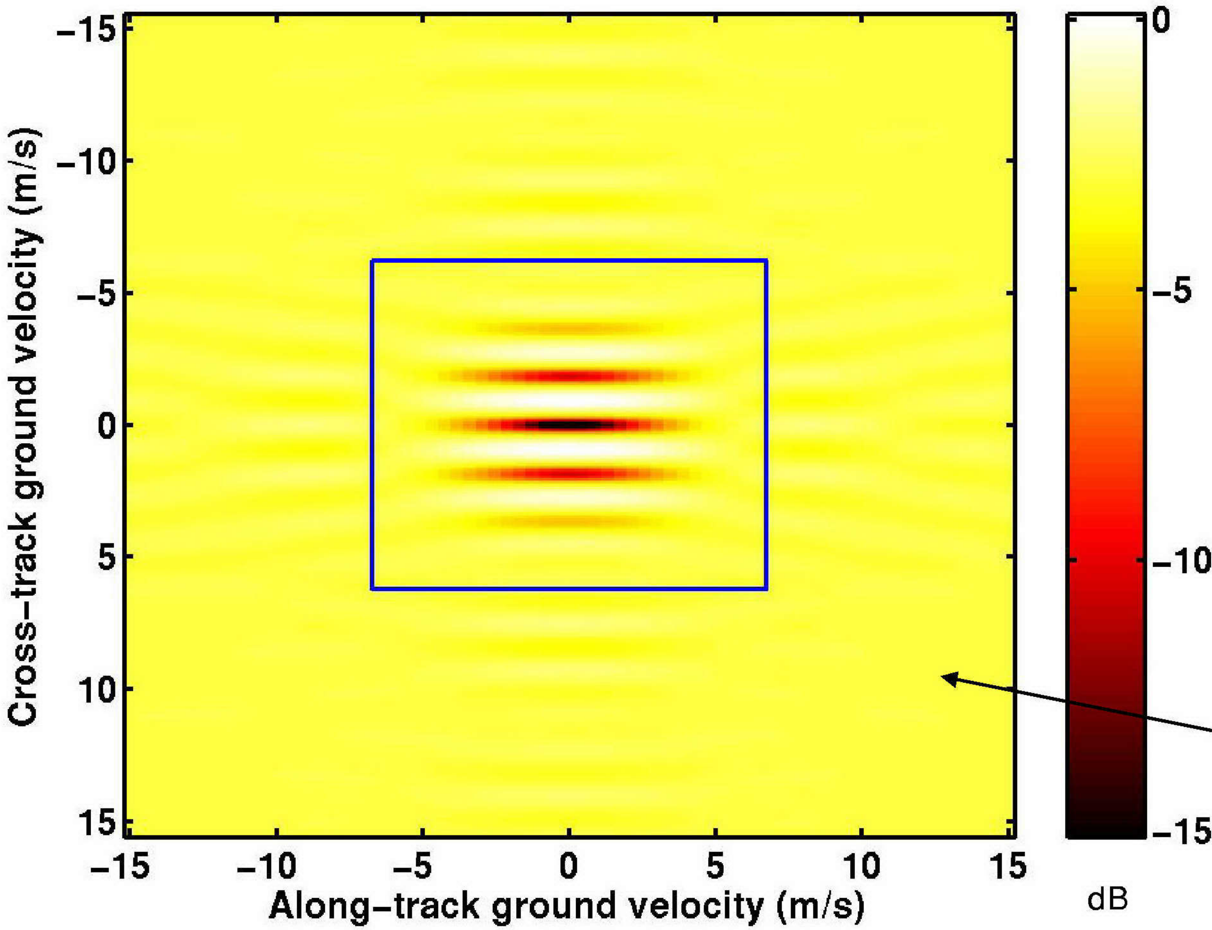


- Carrier = 1 GHz
- Bandwidth = 10 MHz
- CPI = 15 s
- Range = 10 km
- Airspeed = 180 m/s
- Phase center locations = [0,30] m

"Differential SAR" zone:

Target moves > 2 SAR resolution cells over time it takes platform to travel the length of the real aperture

SINR Loss Example

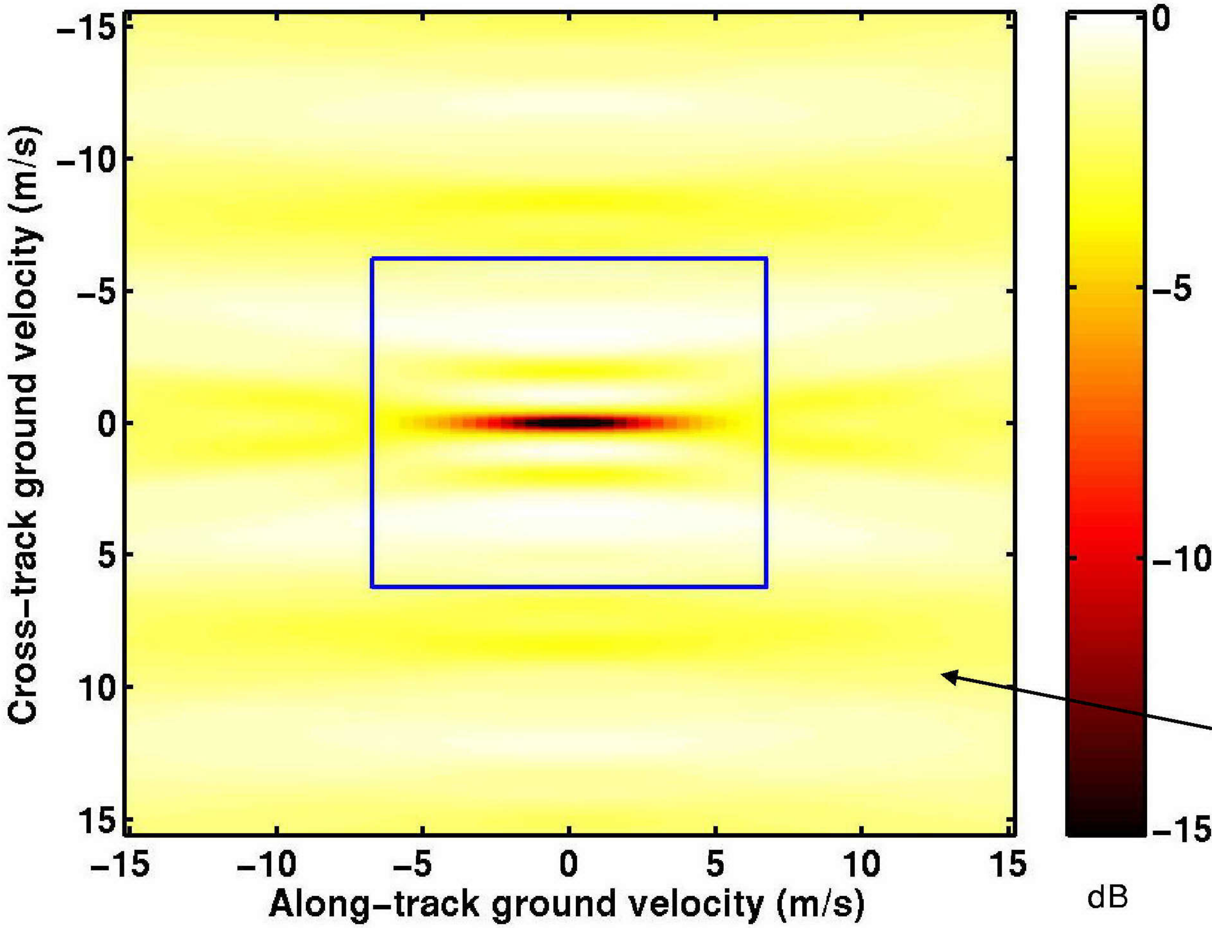


- Carrier = 1 GHz
- Bandwidth = 300 MHz
- CPI = 15 s
- Range = 10 km
- Airspeed = 180 m/s
- Phase center locations = [0,30] m

<u>"Differential SAR" zone:</u>

Target moves > 2 SAR resolution cells over time it takes platform to travel the length of the real aperture

SINR Loss Example



- Carrier = 1 GHz
- Bandwidth = 300 MHz
- CPI = 15 s
- Range = 10 km
- Airspeed = 180 m/s
- Phase center locations = [0,7,30] m

"Differential SAR" zone:

Target moves > 2 SAR resolution cells over time it takes platform to travel the length of the real aperture

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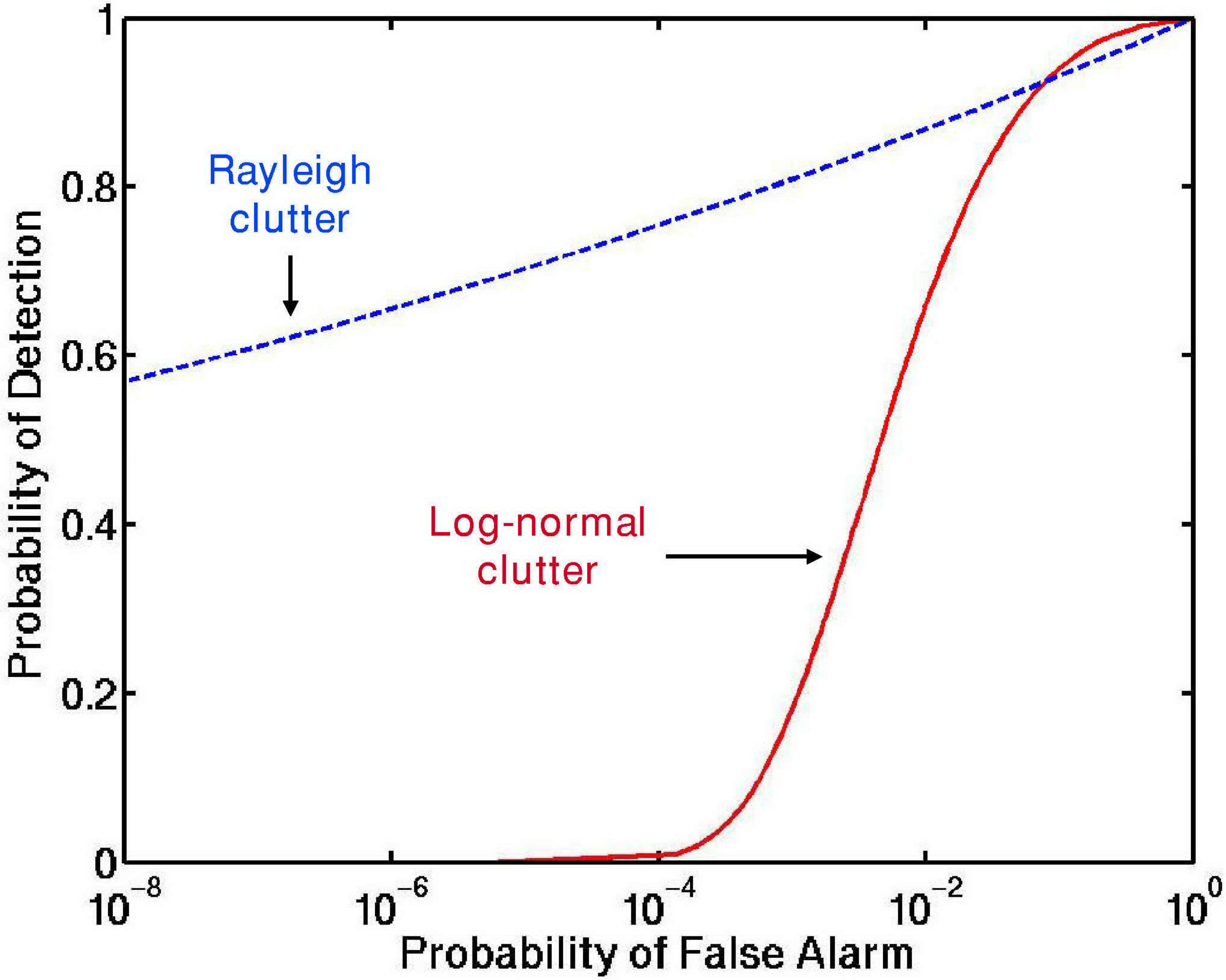
SINR Loss vs. Detection Performance

- SINR loss is a useful diagnostic, but it does not always translate directly into what we care about: detection performance
  - Case in point: SINR loss for stationary targets is infinite, but SAR detects stationary targets quite well!
- WL-GMTI straddles the regime between GMTI-type detection and SAR-type detection
- Need to consider detection theory to understand true capabilities of WL-GMTI

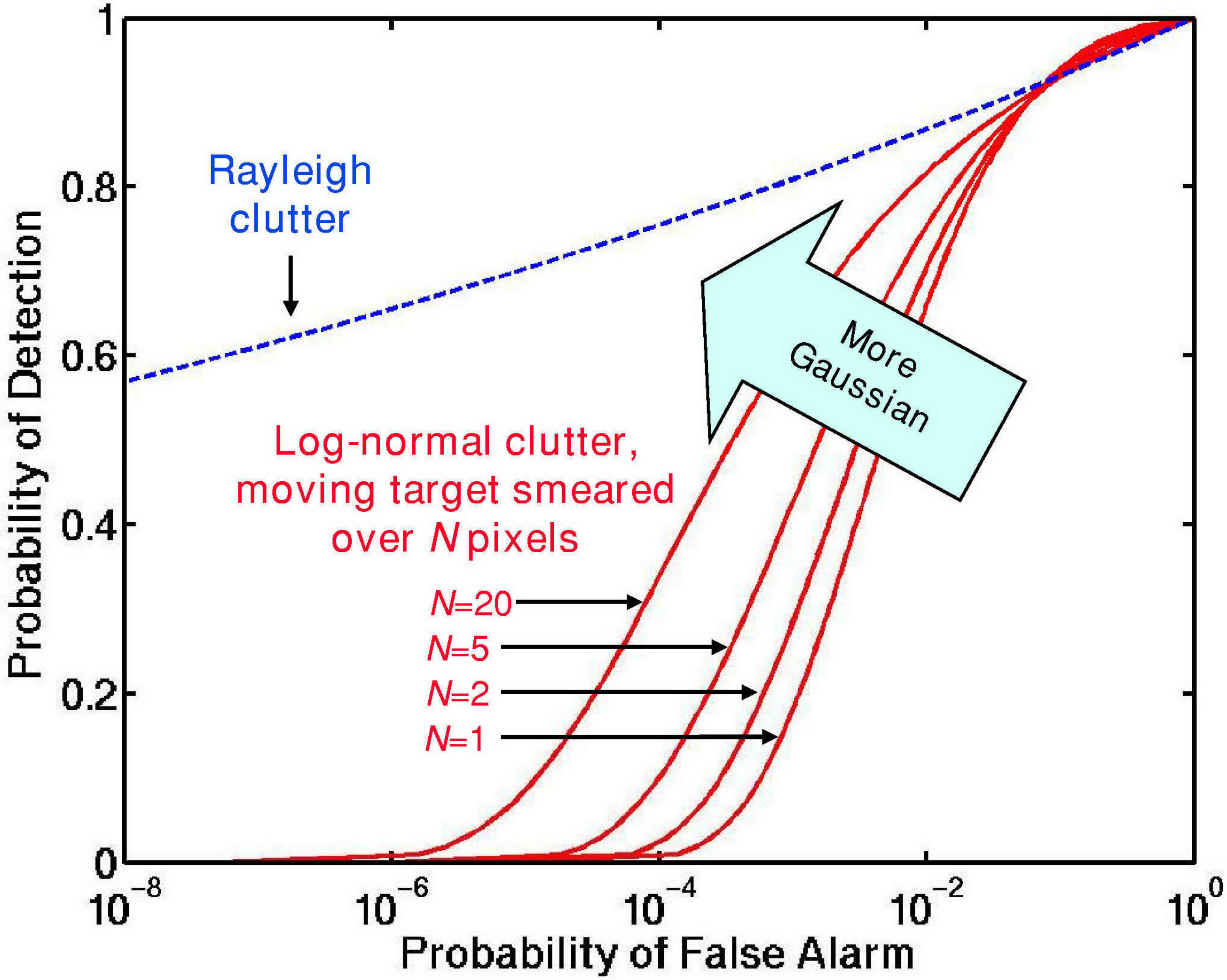
Illustrative Toy Model

- Radar: single-phase center (pure SAR)
- Moving point target with Rayleigh fading
- 15 dB mean target-to-clutter (for focused stationary target)
- Two clutter models:
  - Rayleigh (unrealistic, weak tails)
  - Log-normal (more realistic, heavier tails)

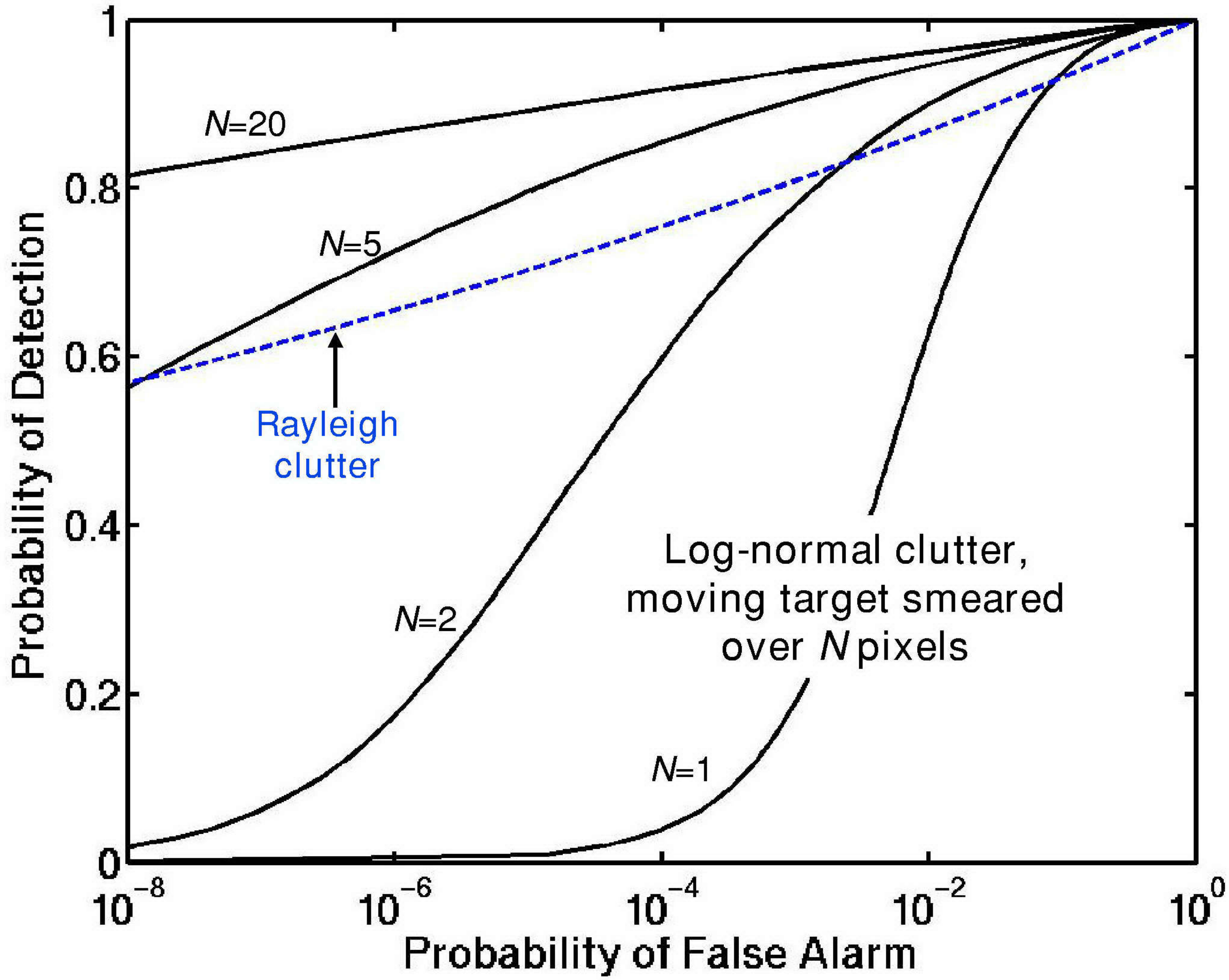
Stationary Target Detection



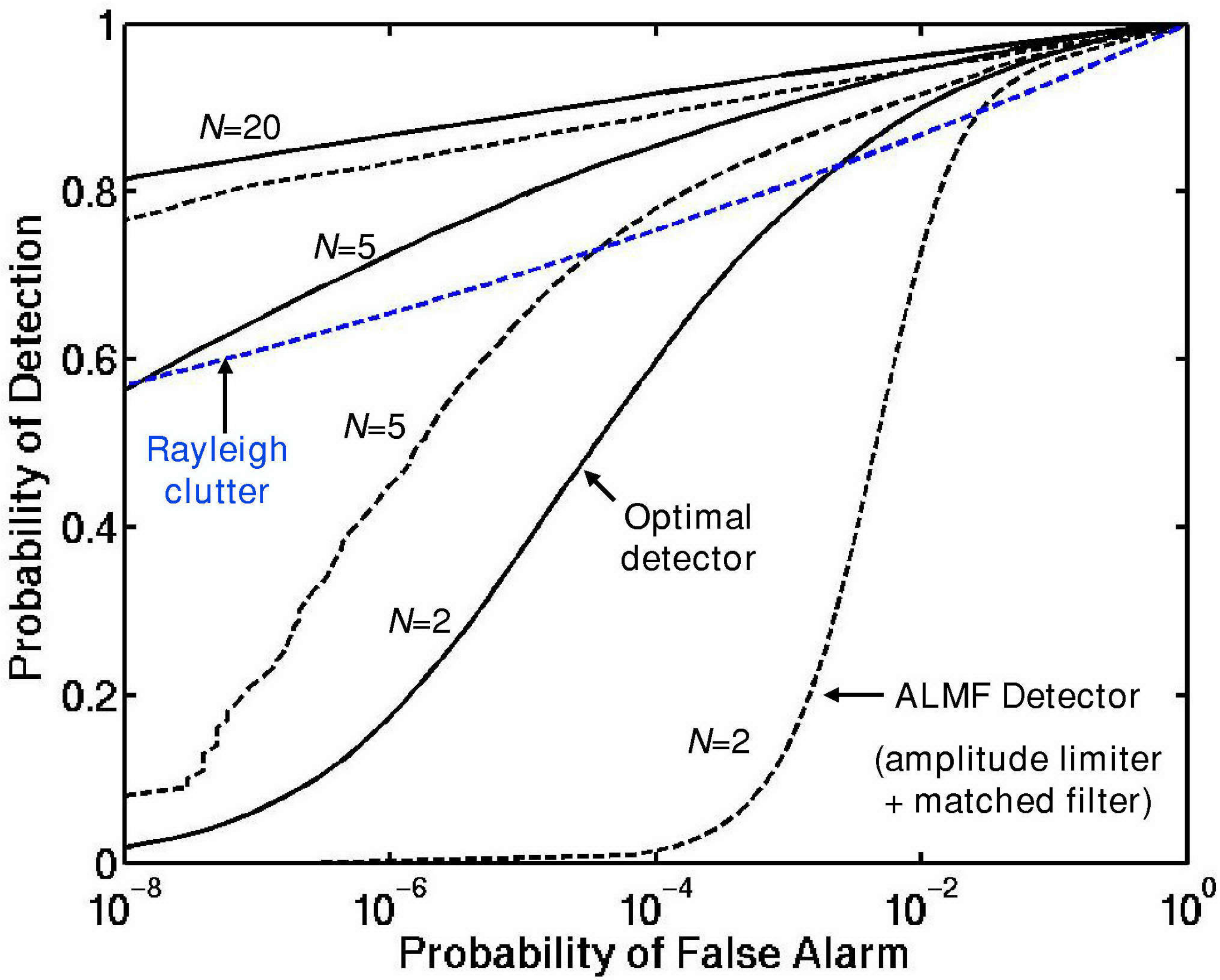
Moving Target: Matched Filter Detector



Moving Target: Bayes-Optimal Detector



Moving Target: ALMF Sub-Optimal Detector



Summary

- Wideband, long-CPI methods offers the promise of detecting slow, low-RCS targets not detectable with traditional GMTI methods
- This talk has explored some basic building blocks for analysis
  – Wideband, long-CPI data model and steering vectors
  – SINR loss analysis
- It appears that the detection capability of WL-GMTI straddles the SAR and GMTI domains: SINR loss alone is not a reliable metric of performance
  – Smearing of target over many pixels can enhance detection in strong-tailed clutter
  – Sub-optimal detector can approach optimal bound
- Many other aspects of the problem are ripe to be explored